A MULTI-WAVELENGTH STUDY OF THE HOT COMPONENT OF THE INTERSTELLAR MEDIUM

NASA Grant No. NAG5-8483

Final Report

For Period 1 June 1999 through 31 March 2003

March 2004

Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, MD 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this Grant is Ronald J. Oliversen, 681.0, Goddard Space Flight Center, Greenbelt, MD 20771

A Multi-Wavelength Study of the Hot Component of the Interstellar Medium

I. Goals

- Using the large number of lines of sight available in the IUE database, identify the lines of sight with high-velocity components in interstellar lines, from neutral species through Si VI, C IV, and N V.
- Compare the column density of the main components (i.e. low velocity components) of the interstellar lines with distance, galactic longitude and latitude, and galactic radial position. Derive statistics on the distribution of components in space (e.g. mean free path, mean column density of a component).
- Examine in detail the lines of sight associated with multiple high velocity, high ionization components, model the shock parameters for the associated superbubble and SNR to provide more accurate energy input information for hot phase models and galactic halo models. Select several regions for further work.
- Obtain higher resolution and multi-wavelength data for the lines of sight with high velocity components (and a few without) to further refine these models.

II. Summary

This research focuses on the kinematics and evolution of the hot phase of the interstellar medium in the Galaxy. The plan was to measure the UV spectra of all hot stars observed with IUE, in order to identify and measure the main component and any high velocity components to the interstellar lines. Collection of data from higher resolution instruments on HST has been proposed for some of the interesting lines of sight.

IUE spectra of 240 stars up to 8 kpc in 2 quadrants of the galactic plane have been examined to (1) estimate the total column density per kpc as a function of direction and distance, and (2) to obtain a lower limit to the number of high velocity components to

the interstellar lines, thus giving an approximation of the number of conductive interfaces encountered per line of sight. By determining an approximation to the number of components per unit distance we aim to derive statistics on interfaces between hot and cold gas in the Galaxy. We find that 20% of the stars in this sample show at least one high velocity component in the C IV interstellar line.

While it was expected that the number of high velocity components detected would increase with distance, assuming a uniform population of supernova remnants, single star bubbles, and superbubbles as well as tunnels or merged structures of hot gas, we find that high velocity features to the interstellar C IV line are generally confined to known supernova remnants and superbubbles, and there is no increase of the interfaces with distance in these 2 quadrants. Although the resolution of IUE of 10,000 is well below current instrumentation, the large number of statistics available with this dataset allow sampling many lines of sight with a photometrically stable detector and provide a guide for future investigation.

Two successful FUSE programs address this research and collected data for several of the lines of sight identified as locations of hot, expanding gas with the IUE data. One FUSE program is complete for the Vela SNR region. Data from another FUSE program to investigate the Cygnus superbubble region are being analyzed.

X-ray data from ROSAT, HST data, and Hα velocity data have been incorporated into analysis.

Using the IUE and FUSE data, a detailed analysis of the shock structures in the Vela SNR has been conducted. An important result is that there is clear evidence that the shock front from the supernova has impacted multiple dense clouds. This is providing an good example of realistic supernova remnant evolution in an inhomogeneous medium and its impact on the physical state of the interstellar medium. Using a Piecewise Parabolic Method numerical hydrodynamics code to model the supernova remnant evolution, the evolution into a non-uniform, clumpy environment is being parameterized.

The investigation of high-velocity components toward the Vela SNR using observations of 54 stars in that line of sight revealed strong high excitation C I lines. The lines are stronger than seen in any other lines of sight in our study of the galactic plane, and imply very high pressure and density values. The presence of these C I high excitation lines is interpreted as evidence of the supernova shock front interacting with dense clouds. Analysis included IRAS data, ROSAT data, and optical data of the region. The submitted paper is included in this report.

Many high velocity features in the higher ionization species were detected in our studies in the line of sight to the Vela SNR. Analysis showed multiple components in many lines of sight, which indicate multiple shock interfaces within the SNR, caused partially be embedded dense clouds in the remnant, and partially from a precursor structure revealed in optical data that is coincident with many of the high-velocity features. Such a precursor structure formed by the star or stellar system before the supernova explosion has never been detected before. The draft paper is included in this report. Further high resolution observations of the precursor structure are planned.

Publications based on work related to the LTSA grant:

"Survey of UV Absorption Line Data of the Galactic Plane", Nichols, J., Slavin, J., & Anderson, C. 2001, AAS Meeting 198, 59.09.

"Absorption Line Studies of the Elongated Cyg OB1 Superbubble", Lauer, J., Nichols, J., & Slavin, J. 2001, AAS Meeting 199, 65.03.

"The Nature of the Vela Supernova Remnant as Revealed by O VI and C IV Absorption Lines", Nichols, J., Slavin, J., & Anderson, C. 2001, AAS Meeting 1999, 126.12.

"FUSE Observations of Highly Ionized Gas in the Vela Supernova Remnant", Slavin, J., Nichols, J., & Blair, W. P. 2004, ApJ, in press.

"Shocked Clouds in the Vela Supernova Remnant", Nichols, J. & Slavin, J. 2004, ApJ, submitted.

"High Velocity Gas in the Line of Sight to the Vela SNR", Nichols, J. & Slavin, J. 2004, in preparation.

"The Frequency and Distribution of High Velocity Gas in the Galactic Plane", Nichols, J., Slavin, J., & Anderson, C. 2004, in preparation.

III. High-Velocity Gas in the Galactic Plane

Data Analysis

All IUE high dispersion spectra of O and B stars in or near the galactic plane (b=+/- 20 degrees) are being analyzed to identify and measure the main and any high velocity components to the interstellar lines. This class of stars was selected because of their strong UV continuum and, in general, lack of stellar features. Here the results of the C IV doublet analysis from 2 galactic quadrants, (2nd and 4th) are presented. The C IV doublet was chosen because it is most likely to indicate shock structures as opposed to H II regions, and to have accurate measurements of equivalent width (the N V is often absent or the continuum in this region has a complicated structure). The analysis includes measurement of the radial velocity of the components and the equivalent width. Only components with an equivalent width of more than 25 mA are considered, based on the resolution of the instrument, implying an upper limit to the detectable log N(C IV) of 12.8. Distances are from Hipparcos, if available. Otherwise, spectrophotometric distances were determined. Column densities have been calculated using a curve of growth analysis. Errors in the measurement of the equivalent widths range from 10% to 30% in most cases, although the errors can be as large as 100% when placement of the continuum was particularly difficult or the spectrum was unusually noisy.

Results

Figures 1-4 plot the galactic position of each star and the symbols are color-coded to indicate the number of high-velocity components detected in the spectrum of the star for C IV. These plots show that the high-velocity components are localized to specific lines of sight that can, in general, be linked to a SNR or OB association.

In spite of the rather low sensitivity of IUE compared with current instrumentation, the wealth of targets provides a large number of statistics that can be useful in identifying trends and placing upper limits on the column densities of shock interfaces in the galactic plane.

The fact that multiple components are generally confined to known SNR and OB associations suggests that interfaces between the hot and warm or cold phases of the galactic ISM are either few in number, aside from the known SNR and superbubbles, or have column densities below detectability with IUE. We will explore this issue by examining a few spectra of the more distant stars in our IUE sample from more sensitive instrumentation. The upper limit of column density for high velocity components constrains the theories of distribution and evolution of the hot phase of the ISM.

Figure 5 is a plot of the distance to the star vs. the C IV column density. Only stars for which the C IV doublet ratio is greater than 1.0 have been included. The mean density for the stars with d $\leq$ 3000 is 4.3 x 10^{-8}, an order of magnitude smaller than that found by Savage and Massa. This discrepancy could be due to a systematic difference in the method of measuring the equivalent width. Our larger sample of stars may also play a role. Also, we have used Hipparcos distances, which tend to be smaller than the spectrophotometric distances for this group of stars.

Figures 6 shows the number of interstellar line components in C IV as a function of C IV column density. No clear trend emerges here, contrary to our original concept that high velocity structures would tend to increase with length of the line of sight.

It was concluded that, at least for this limited dataset and the resolution of the IUE instrument, that high velocity gas is generally confined to known supernova remnants and superbubbles in the Galaxy. Other cooling interfaces of the hot phase of the ISM must have radial velocities of less than 25 km/s relevant to the LSR, implying older structures. There are a few lines of sight that show high velocity C IV features that are not associated with known supernova remnants or OB associations.

Figure 1: Position of the target stars in galactic coordinates for the 2nd galactic quadrant. Stars with spectra showing no high velocity components are indicated in black. Those with high velocity components are indicated in red. Note the clustering of the high velocity

components in several regions.

Figure 2: Position of the target stars showing high velocity C IV components in galactic coordinates for the 2nd galactic quadrant. The number of high velocity components toward each star is indicated by the color.

Figure 3: Position of the target stars in galactic coordinates for the 4th quadrant. Stars with spectra showing no high velocity components are indicated in black. Those with high velocity components are indicated in red. Note the clustering of the high velocity components in several regions.

Figure 4: Position of the target stars showing high velocity C IV components in galactic coordinates for the 4th galactic quadrant. The number of high velocity components toward each star is indicated by the color.

Figure 5: Distance to the target stars vs. total C IV column density. The data have been fit for the complete sample, and also for those stars with distance less than 3000 pc, due to the scarcity of data at greater distances. The mean C IV density is indicated for both of these cases.

Figure 6: C IV total log column density plotted against number of components detected in the C IV line. Lines of sight with log column density greater than 15 have been identified as stars in supernova remnants and OB associations.

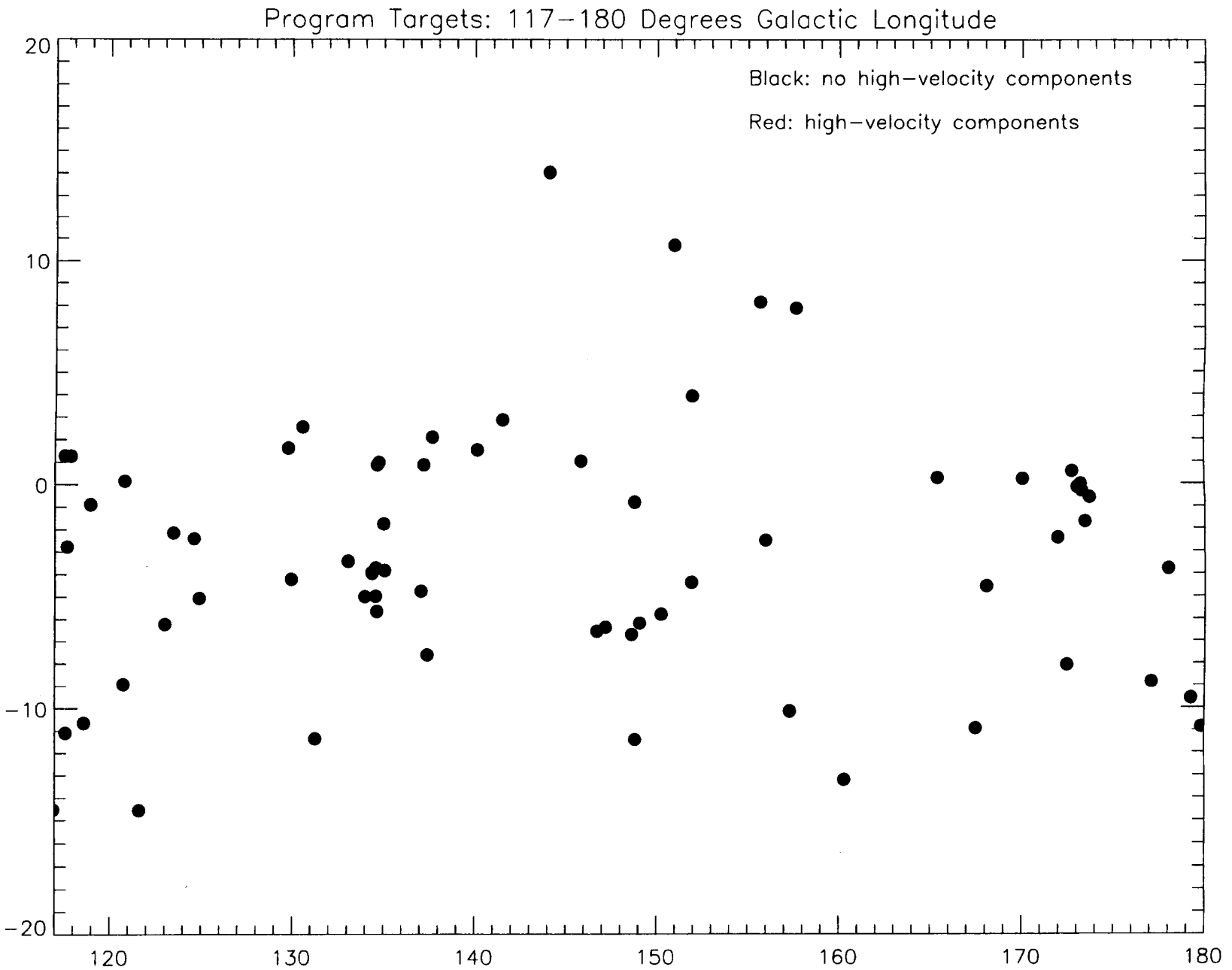
Program Targets: 117–180 Degrees Galactic Longitude
Black: no high–velocity components
Red: high–velocity components
20
10
0
−10
−20
120
130
140
150
160
170
180

FIGURE 1

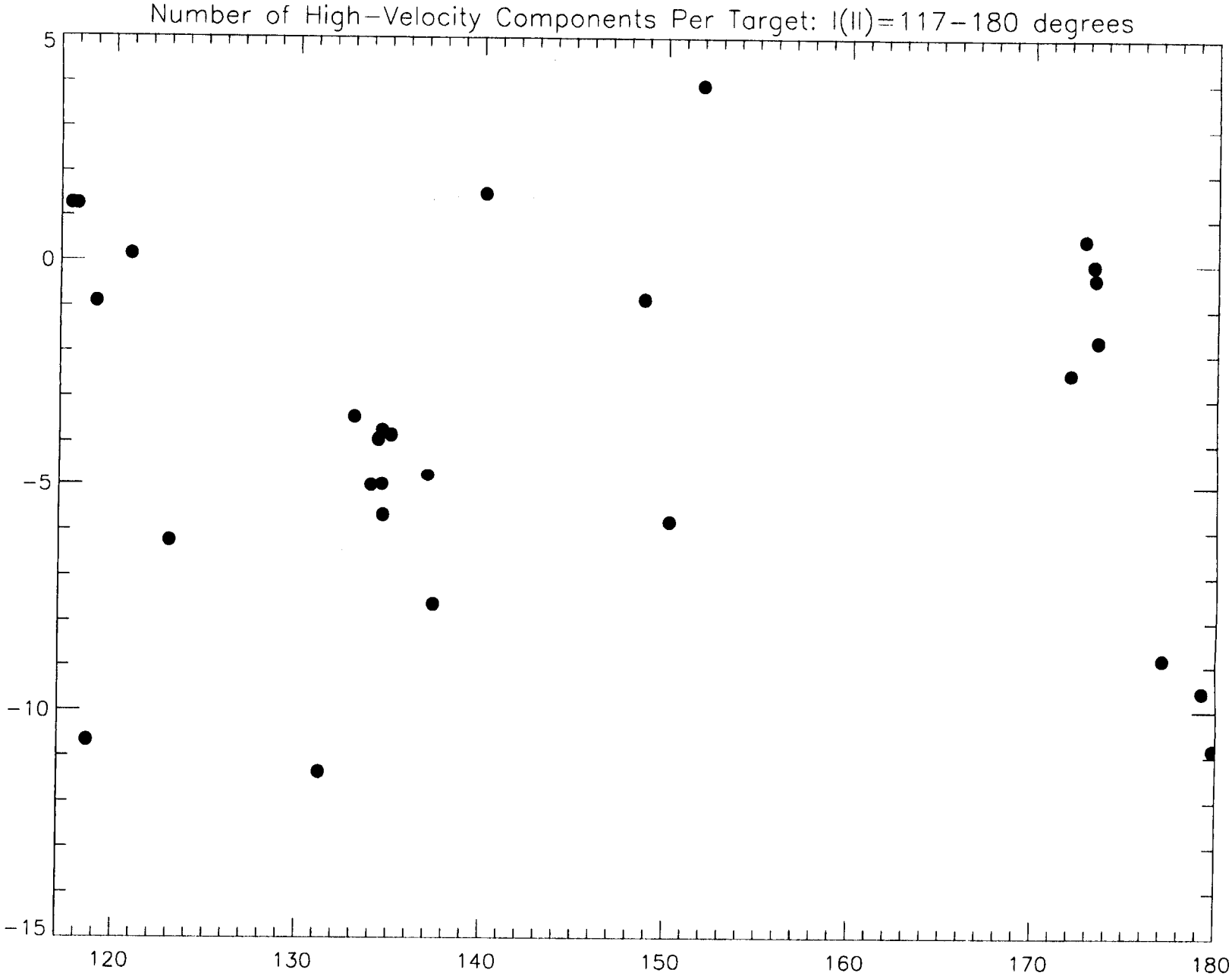
Number of High-Velocity Components Per Target: l(II)=117-180 degrees
5
0
-5
-10
-15
120
130
140
150
160
170
180

FIGURE 2

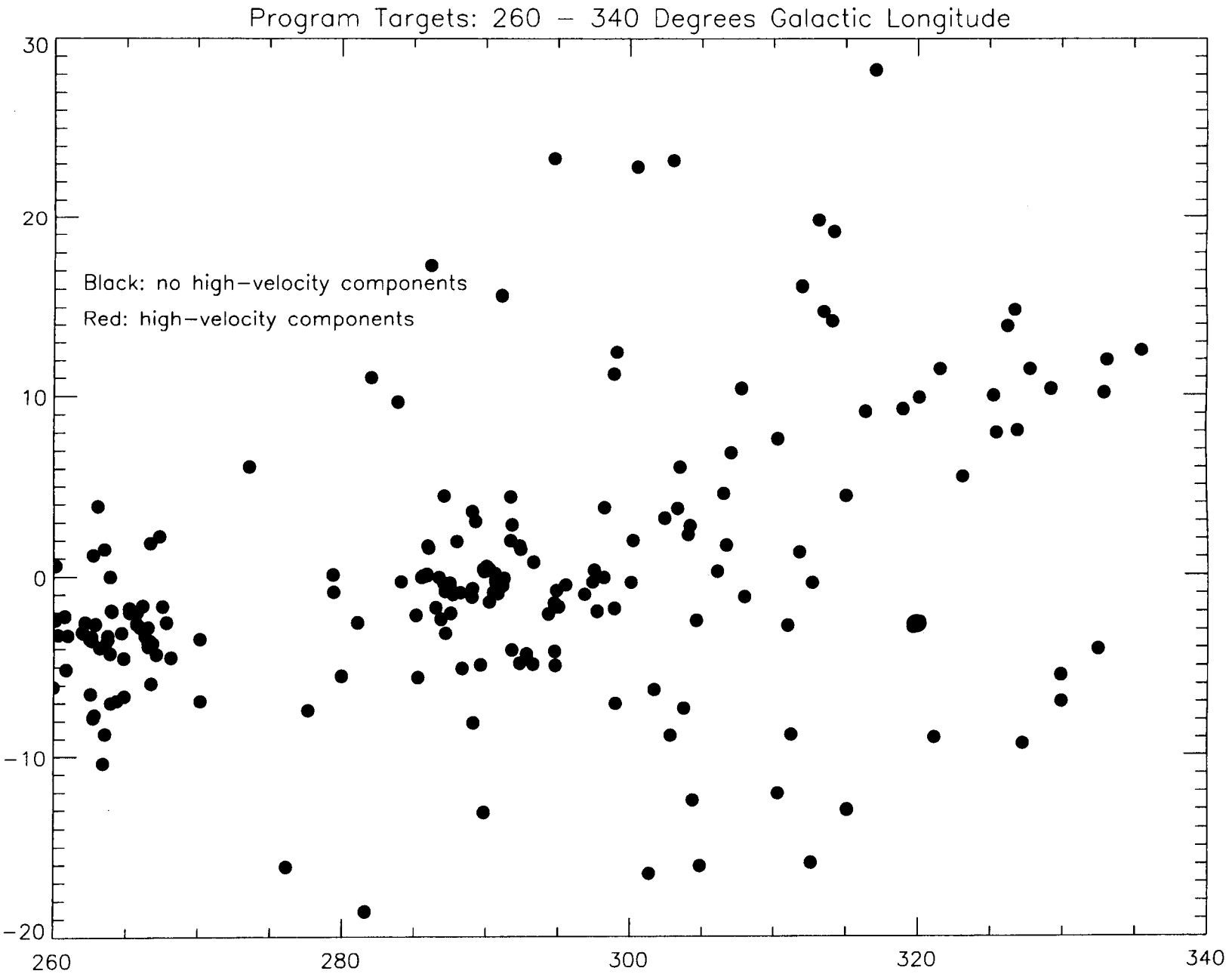
Program Targets: 260 – 340 Degrees Galactic Longitude
Black: no high–velocity components
Red: high–velocity components
30
20
10
0
−10
−20
260
280
300
320
340

FIGURE 3

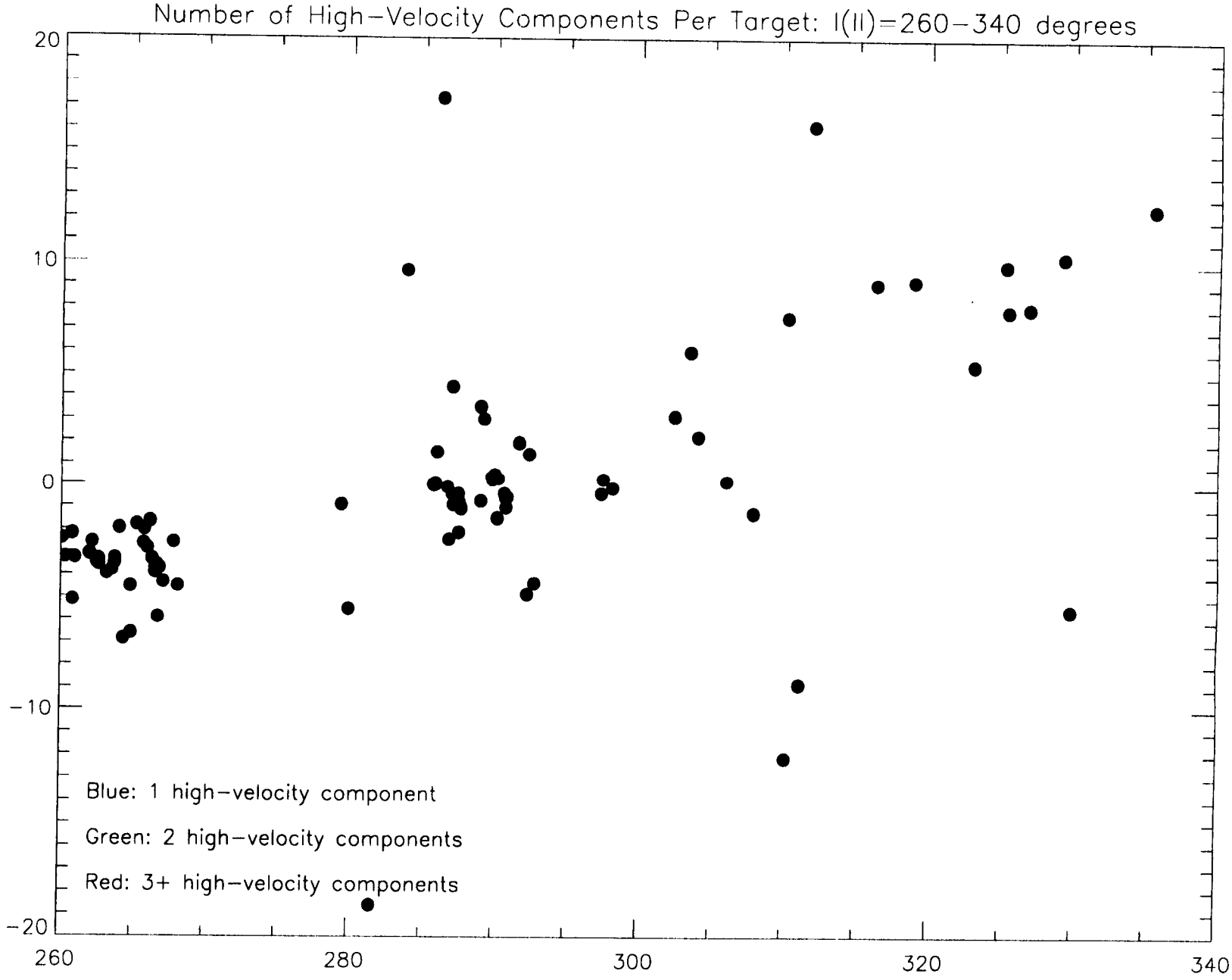
Number of High-Velocity Components Per Target: l(II)=260-340 degrees
20
10
0
-10
-20
260
280
300
320
340
Blue: 1 high-velocity component
Green: 2 high-velocity components
Red: 3+ high-velocity components

FIGURE 4

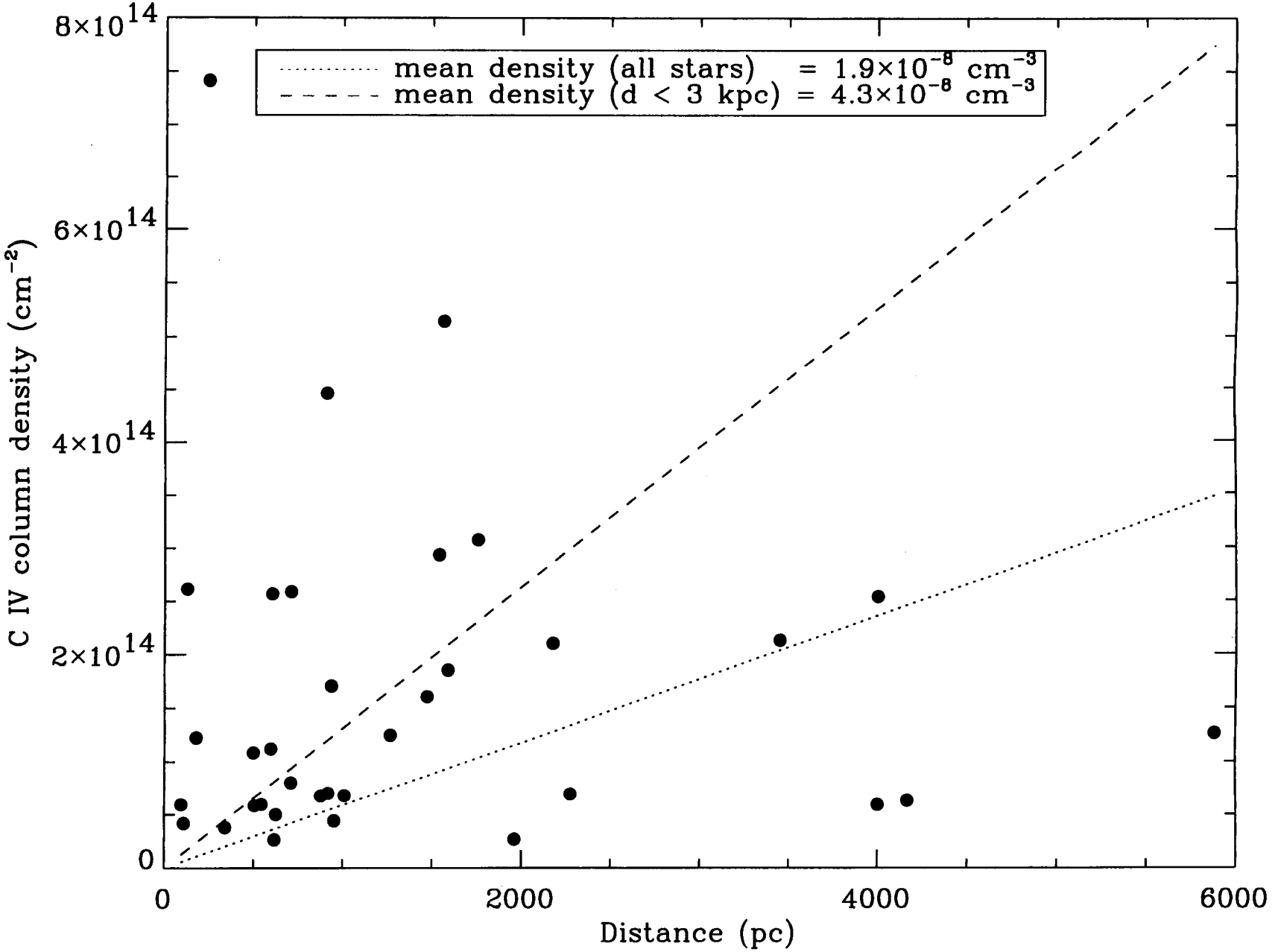
mean density (all stars) = 1.9×10⁻⁸ cm⁻³
mean density (d < 3 kpc) = 4.3×10⁻⁸ cm⁻³
C IV column density (cm⁻²)
8×10¹⁴
6×10¹⁴
4×10¹⁴
2×10¹⁴
0
0
2000
4000
6000
Distance (pc)

FIGURE 5

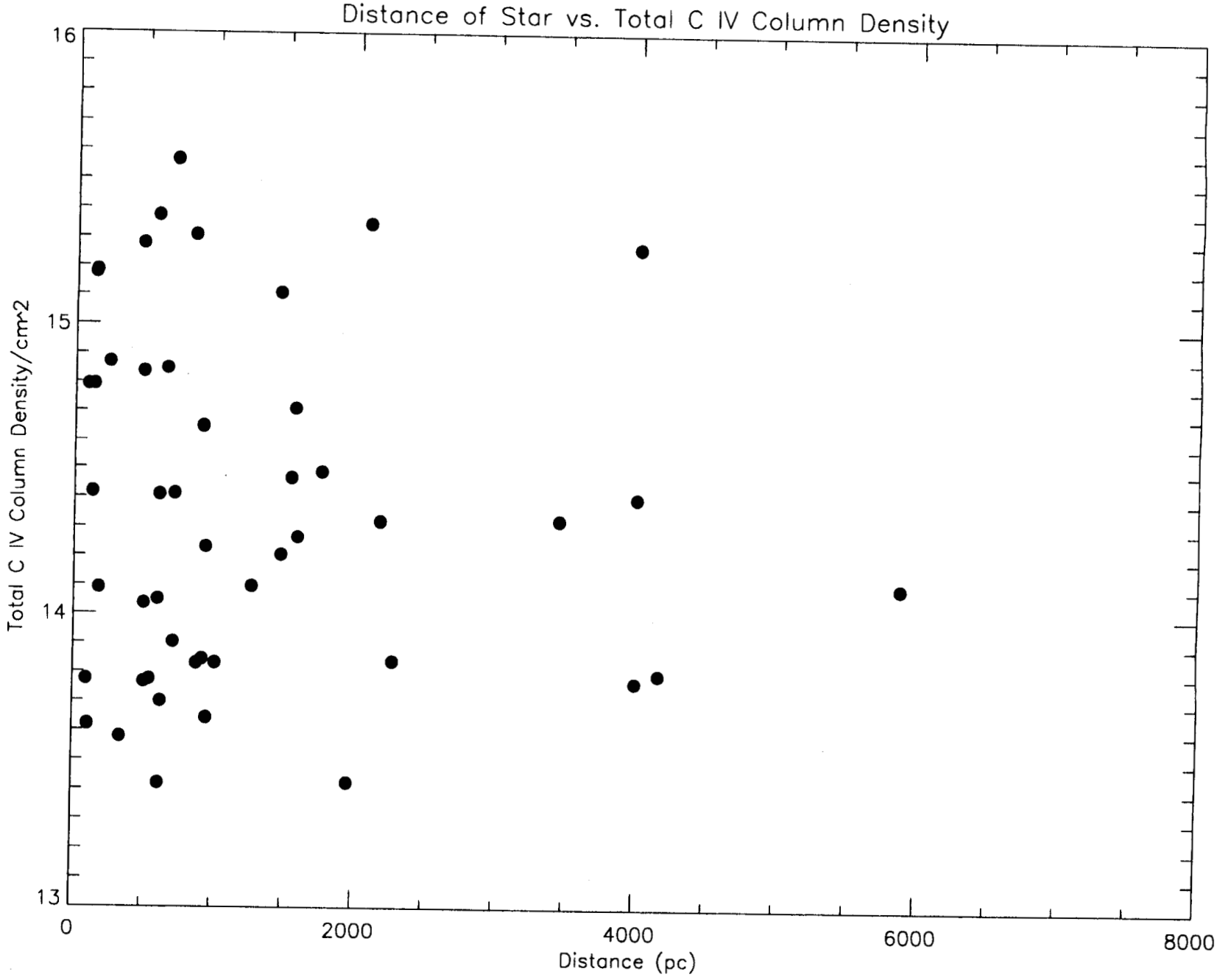
Distance of Star vs. Total C IV Column Density
Total C IV Column Density/cm^2
16
15
14
13
0
2000
4000
6000
8000
Distance (pc)

FIGURE 6